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The correlation between black hole mass and bulge velocity dispersion in hierarchical galaxy formation models

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ABSTRACT

Recent work has demonstrated that there is a tight correlation between the mass of a black hole and the velocity dispersion of the bulge of its host galaxy. We show that the model of Kauffmann & Haehnelt, in which bulges and supermassive black holes both form during major mergers, produces a correlation between $M_{\rm bh}$ and σ with slope and scatter comparable to the observed relation. In the model, the $M_{\rm bh} - \sigma$ relation is significantly tighter than the correlation between black hole mass and bulge luminosity or the correlation between bulge luminosity and velocity dispersion. There are two reasons for this: i) the gas masses of bulge progenitors depend on the velocity dispersion but not on the formation epoch of the bulge, whereas the stellar masses of the progenitors depend on both; ii) mergers between galaxies move black holes along the observed $M_{\rm bh} - \sigma$ relation, even at late times when the galaxies are gas-poor and black holes grow mainly by merging of pre-existing black holes. We conclude that the small scatter in the observed $M_{\rm bh} - \sigma$ relation is consistent with a picture in which bulges and black holes form over a wide range in redshift.

Key words: black hole physics — galaxies: formation — galaxies: nuclei quasars: general.

1 INTRODUCTION

Several recent papers have shown that a surprisingly tight correlation exists between the masses of supermassive black holes and the velocity dispersions of the bulges which host them. Ferrarese & Merritt (2000) re-analyzed published samples of black hole mass estimates, showing that if the analysis is restricted to 12 galaxies with reliable black hole mass measurements, the correlation is extremely good, with $M_{\rm bh} \propto \sigma^{5.27\pm(0.4)}$. Gebhardt et al. (2000a) report a similar relation with a somewhat shallower slope, $M_{\rm bh} \propto \sigma^{3.75(\pm0.3)}$, and a scatter of only 0.3 dex, based on a sample of 26 galaxies, including 13 new black hole mass estimates derived using Hubble Space Telescope spectra. In a second paper, Gebhardt et al. (2000b) demonstrate that black holes with reverberation mapping mass estimates also fall on the same relation.

The tightness of this new correlation greatly increases confidence in the accuracy of the observed black hole mass estimates. It also strengthens theoretical arguments that spheroid formation and the growth of black holes are closely linked (Richstone et al. 1998; Cattaneo, Haehnelt & Rees 1999; Kauffmann & Haehnelt 2000 (KH2000); Monaco, Salucci & Danese 2000; Cavaliere & Vittorini 2000). Cattaneo et al. (1999) and KH2000 demonstrated that the $M_{\rm bh} - L_{\rm bulge}$ relation and the scatter reported by Kormendy & Richstone (1995) and Magorrian et al. (1998) is well reproduced in phenomenological models of galaxy formation in hierarchical cosmogonies. In this Letter, we analyze the relation between black hole mass and bulge velocity dispersion in the KH2000 model. We assume a ΛCDM cosmology with $\Omega_{\rm mat} = 0.3$, $\Omega_\Lambda = 0.7$, $h = 0.65$, $\sigma_8 = 1$ throughout.

2 THE FORMATION AND GROWTH OF SUPERMASSIVE BLACK HOLES DURING MAJOR MERGERS

In cold dark matter (CDM)-like cosmologies, galaxies form in a hierarchy of merging halos (e.g. White & Rees 1978; White & Frenk 1991). The formation and evolution of galaxies in such a picture has been studied in considerable detail using Monte-Carlo realizations of the hierarchical growth of structure, which include simple prescriptions to describe gas cooling, star formation and supernova feedback (see Kauffmann et al 1999; Somerville & Primack 1999; Cole et al 2000 for a selection of recent results).

Below we summarize the main features of the model described by KH2000, who constructed a unified model for the formation and evolution of galaxies, supermassive black holes and QSOs. In their model, the quiescent accretion of cooling gas from a halo results in the formation of a disk.

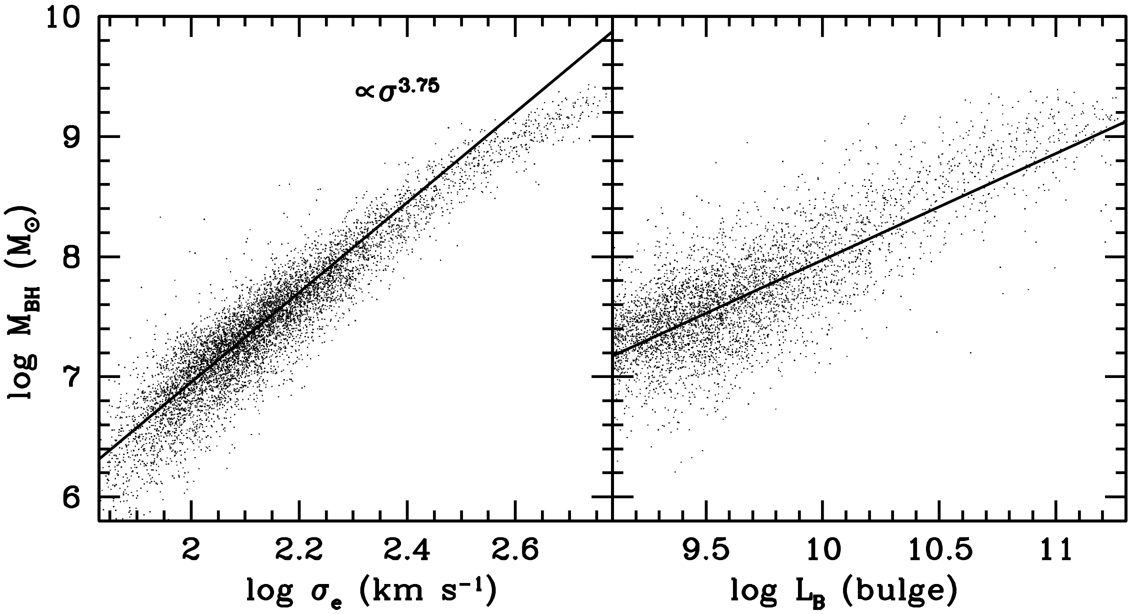

Figure 1. Black hole mass *vs* bulge velocity dispersion (left) and bulge luminosity (right). Solid lines are the fits to an observed sample by Gebhardt et al. (2000).

The fraction of cold gas in the disk that forms stars over one dynamical time is assumed to scale with redshift as $(1+z)^{-3/2}$. This assumption was required in order to fit the observed decline in the total content of cold gas in galaxies towards low redshift inferred from observations of damped Lyman-alpha systems (Storrie-Lombardi et al. 1996). If two galaxies of comparable mass merge, a spheroid forms and the remaining gas is transformed into stars in a "starburst". The same major mergers are responsible for the formation and fuelling of black holes in galactic nuclei. During the merger the central black holes of the progenitors coalesce and a fraction of the available cold gas is accreted by the black hole. The accreted fraction is assumed to scale with the circular velocity $v_{\rm c}$ of the surrounding dark matter halo as $(1 + (280/v_{\rm c})^2)^{-1}$ (This scaling was adopted in order to fit the slope of the $M_{\rm bh} - L_{\rm bulge}$ relation of Magorrian et al (1998).)

The only change in this Letter compared to KH2000 is a reduction by a factor of three in the fraction of gas assumed to accrete onto the black hole. This is needed because the mass estimates of black holes from the new data are significantly smaller than those of Magorrian et al (1998). In the KH2000 model, black holes grew in mass only during major mergers. As pointed out previously, it is certainly possible that supermassive black holes have more complicated accretion histories (see Haehnelt, Natarajan & Rees 1998 and Haehnelt & Kauffmann 2000 for a detailed discussion). Other accretion modes could easily be incorporated into the model. We note, however, that the recent reduction in the estimated total mass density in black holes makes arguments for accretion modes other than those traced by optical- and infrared-bright QSOs less compelling.

3 THE BLACK HOLE MASS – BULGE VELOCITY DISPERSION RELATION

Fig. 1a shows scatterplots of black hole mass versus bulge velocity dispersion in our models. We do not have a dynamical model for computing σ for the bulges in our simulations. For simplicity, we have assumed a constant ratio $v_{\rm c}/\sigma$, where $v_{\rm c}$ is the circular velocity of the halo in which the bulge found itself after its last major merger. It is easy to show that any well-mixed population of stars orbiting within an isothermal potential must satisfy $v_{\rm c}/\sigma = \sqrt{2}$. Following Kauffmann & Charlot (1998), we choose the ratio of $v_{\rm c}/\sigma$ to reproduce the zero point of the observed Faber-Jackson relation (see Fig. 2). To fit the observations, we require $v_{\rm c}/\sigma \sim 2$.

The thick solid line in fig. 1a ($M_{\rm bh} \propto \sigma^{3.75}$) shows the relation derived by Gebhardt et al. (2000a), which is reproduced very well. In the models, the total mass of gas that cools in a halo scales roughly as σ^3. Feedback effects steepen the relation to approximately $M_{\rm bh} \propto \sigma^4$, but feedback would have to be more extreme in order to obtain a correlation as steep as $M_{\rm bh} \propto \sigma^{5.3}$ (Ferrarese & Merritt 2000). The scatter in the relation is 0.2 dex, somewhat smaller than the 0.3 dex reported by Gebhardt et al. which include measurement errors. Fig. 1b shows the black hole mass – bulge luminosity correlation compared with the observed relation in the Gebhardt et al. sample. For the simulated galaxies, the scatter is about a factor two larger and again agrees well with the observational data. The large scatter in the relation in Fig. 1b is a consequence of the large dispersion in the relation between the luminosities and velocity dispersions of bulges. This is illustrated in in Fig 2a where we plot the $L_{\rm bulge} - \sigma$ (Faber-Jackson) relation for the elliptical galaxies in our model. Elliptical galaxies are defined as those objects with a ratio of bulge to total luminosity greater than 0.4 in the B-band. In the next section, we study the origin of the scatter in these relations and explain why the scatter in the

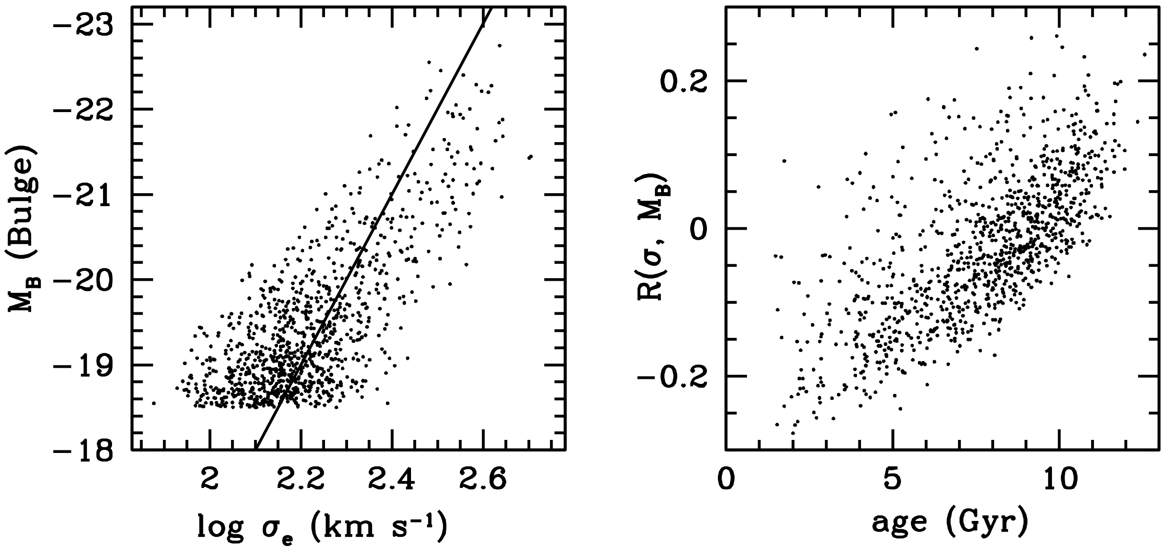

Figure 2. *Left:* The Faber-Jackson relation between bulge absolute magnitude in the B-band and stellar velocity dispersion. The solid line is the relation $\log \sigma = -0.102 M_B + 0.24$ obtained by Forbes & Ponman (1999) from their best fit to the elliptical galaxies in the sample of Prugniel & Simien (1996) *Right:* The residuals $R(\sigma, M_B) = \log \sigma + 0.102 M_B - 0.24$ in the Faber-Jackson relation as a function of the age of the bulge.

$M_{\rm bh} - \sigma$ relations is significantly smaller than that of the $L_{\rm bulge} - \sigma$ or $M_{\rm bh} - L_{\rm bulge}$ relations.

4 THE SCATTER IN THE $M_{\rm BH} - \sigma$ RELATION

Previous work has demonstrated that hierarchical galaxy formation models succesfully reproduce the Faber-Jackson ($L_{\rm bulge} - \sigma$) and the Magorrian ($M_{\rm bh} - L_{\rm bulge}$) relations (Kauffmann & Charlot 1998, KH2000). The slopes of these correlations are determined by how much gas is able to cool and forms stars or is funneled to the centre in a dark matter halo of given mass or circular velocity. This is set by the assumed balance between gas cooling, star formation, supernova feedback and accretion in the halos. The correlations are tight for bulges that form at fixed epoch, but the scatter increases substantially if the galaxy population as a whole is considered. This is demonstrated by Fig. 2b, where we plot the residuals in our "Faber-Jackson" relation as a function of the age of the bulge. Age is defined as the time elapsed since the bulge had its last major merger. As can be seen, the residuals in the Faber-Jackson relation correlate strongly with age: young bulges of fixed velocity dispersion are brighter than old bulges. Our results are in good agreement with those of Forbes & Ponman (1999), who study residuals in the Faber-Jackson relation for a sample of 88 nearby ellipticals with ages determined from absorption line spectroscopy. KH2000 showed that a similar effect is expected for the $M_{\rm bh} - L_{\rm bulge}$ relation. Young bulges of fixed luminosity contain less massive black holes than older bulges. This prediction was recently confirmed by Merrifield, Forbes & Terlevich (2000).

Why does the $M_{\rm bh} - \sigma$ relation exhibit such small scatter? In Fig. 3a, we show how the gas and the stellar masses of bulge progenitors vary as a function of the formation redshift of the bulge. Results are shown for bulges with $\sigma = 150$ km s^{-1} and $\sigma = 200$ km s^{-1}. The cold gas masses of the progenitors of bulges of given velocity dispersion *are essentially independent of redshift*, whereas their stellar masses decrease at high redshift. As discussed by KH2000, this decrease in the ratio of gas mass to stellar mass in galaxies is crucial for explaining the observed rapid decline of the QSO activity at late times, as well as the decrease in the total content of cold gas in galaxies inferred from damped Lyα systems (Storrie-Lombardi et al. 1996).

In our model the amount of gas available for accretion onto a black hole during a major merger depends only on the velocity dispersion of the bulge and not on redshift. This together with our assumption that a fixed fraction of this gas is accreted by the black hole accounts for the small scatter in the $M_{\rm bh} - \sigma$ relation for bulges forming in gas-rich mergers.

What about gas-poor mergers, where gas accretion contributes little to the growth of the black hole? Such gas-poor mergers are important for massive bulges forming at late times (KH2000). Figure 3b shows "evolutionary tracks" in the $M_{\rm bh}{-}\sigma$ plane for 20 black holes in our model with masses $\sim 10^9 M_\odot$. These black holes typically form in 3-5 merging events spaced quite widely in redshift. At late times, the host galaxies of these black holes have rather small cold gas fractions. Nevertheless, it is clear from our plot that black holes always move along the correlation as they merge, even for massive systems at late times. The latter can be understood as follows. Let us consider the case where black holes grow only by merging and therefore have masses that scale in proportion to those of their host halo. For halos of constant characteristic density, the velocity dispersion σ scales $\propto M_{\rm halo}^{1/3}$. With decreasing redshift the characteristic density decreases and the velocity dispersion grows more slowly with increasing mass: $\sigma \propto \rho^{1/6} M_{\rm halo}^{1/3}$. In CDM-like cosmogonies the characteristic mass of typical dark matter haloes scales as $\propto \rho^{-2/(3+n)}$, where n is the effective slope of the DM fluctuation spectrum. At galaxy scales $n \sim -2$. This gives a scaling $M_{\rm bh} \propto \sigma^4$.

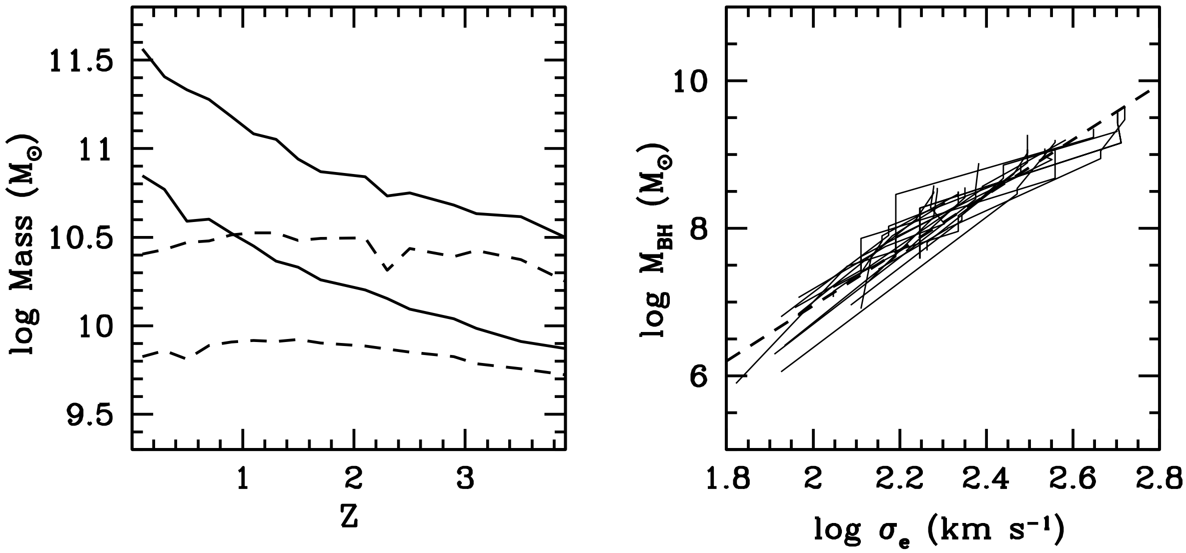

Figure 3. *Left:* Gas (dashed curves) and stellar (solid curves) masses of bulge progenitors as a function of formation redshift for bulges with $\sigma = 150$ km s^{-1} (lower curves) and 200 km s^{-1} (upper curves). *Right:* "Tracks" of bulges in the black hole mass bulge velocity dispersion plane. The dashed line is the observed relation from Gebhardt et al. (2000a).

5 DISCUSSION AND CONCLUSIONS

We have demonstrated that the model of KH2000 where supermassive black holes are formed and fuelled during major mergers produces a tight correlation between black hole mass and bulge velocity dispersion very similar to that observed by Gebhardt et al. (2000a). The model also reproduces the observed relation between black hole mass and bulge luminosity, as well as the relation between bulge luminosity and bulge velocity dispersion.

In the model, the slopes of these relations are determined by how much gas cools, forms stars or is funneled to the centre in dark matter halos of different mass/velocity dispersion. Adopting simple, but physically plausible prescriptions to describe these processes, we are able to fit all three relations simultaneously. Note that the only change we have made compared to KH2000 is an overall reduction of the accreted gas fraction.

The large scatter in the $M_{\rm bh} - L_{\rm bulge}$ and the $L_{\rm bulge} - \sigma$ relations is primarily a consequence of the wide range in redshift over which bulges and supermassive black holes form. The stellar mass of a bulge of fixed velocity dispersion depends strongly on when the bulge formed. Bulges that form early are less massive than bulges that form late. Note that the same is true of disk galaxies in our model. These predicted correlations with age appear to be supported by the available data.

Nevertheless, the scatter in the $M_{\rm bh} - \sigma$ relation is small. There are two reasons for this.

- The amount of gas accreted by a black hole during the formation of a bulge of fixed velocity dispersion does not depend on redshift. In our model, disk galaxies of given circular velocity contain about the same amount of gas at all redshifts. This is a further prediction of the model to be tested by future observations.
- The frequent merging of galaxies in hierarchical cosmogonies moves galaxies along the correlation in the $M_{\rm bh} - \sigma$ plane, even when galaxies are gas-poor and their black holes grow mainly by the merging of preexisting black holes.

The model of KH2000 is a supply-limited model for the accretion history of supermassive black holes. We note that the model does not allow for any dependency in the amount of gas accreted by the black hole on the orbital parameters of the merger. We have also assumed a fixed scaling between the velocity dispersion of a bulge and the circular velocity of the halo in which it resides. These are all potential sources of additional scatter. Detailed numerical simulations will be needed to decide whether a physical mechanism that depends on the bulge potential and that limits the growth of supermassive black holes is required to keep the correlation tight. From our present analysis, we conclude that the tightness of the observed correlation is in apparent agreement with a scenario in which merging events produce supermassive black holes and bulges over a wide range in redshift.

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